

GP-303187

**METHOD AND SYSTEM FOR
DETERMINING TIRE PRESSURE IMBALANCES**

RELATED APPLICATION

[0001] This application is a continuation of U.S. Serial No. 10/347,151 filed January 17, 2003.

5 TECHNICAL FIELD

[0002] This invention relates to a method of and system for determining imbalances in tire pressure on vehicles equipped with wheel rotation sensors.

10 BACKGROUND OF THE INVENTION

[0003] Some suppliers of automotive chassis control systems offer algorithms that use wheel speed for pneumatic tire inflation monitoring. The typical wheel speed based tire inflation-monitoring algorithm resides within an anti-lock brake controller. This system architecture is required because of the need for high resolution and high wheel speed data throughput. These systems rely on accurate microprocessor timer information to perform the required speed calculations. The measured time between speed ring teeth is used to calculate wheel speed and wheel slip. Due to the nature of these calculations, such systems are prone to noisy data at low and high speeds, under some road conditions, due to imprecise machining of speed ring teeth, and microprocessor timing limitations. A typical wheel speed based system may operate well while traveling in a straight line, at steady speeds, and on smooth surfaces, but exhibit a high rate of false warnings when conditions are not optimal.

SUMMARY OF THE INVENTION

[0004] While a vehicle is in motion, the present invention determines when any combination of one, two, or three wheels are in a state of rotational error through an adaptive measurement of the distance that the four wheels

5 have traveled and not through any calculation of wheel speed. This invention has the inherent ability to accurately discern a measure of pneumatic tire pressure imbalance in a way not yet achieved.

[0005] More precisely, this invention provides a means to accurately monitor tire pressure imbalance through the measurement of distance by way

10 of digital pulse devices included in existing anti-lock braking systems and vehicle transmissions. Moreover, this invention does not use nor care about the measured time between digital pulses and will operate at the lowest possible speed at which a digital pulse may be sensed. This invention will operate and maintain accuracy equally as well at unrestricted high speeds.

15 This invention will operate expediently on any surface. Tire pressure imbalance is determined while all four wheels are on a similar surface. Furthermore, this invention is able to detect certain surfaces such as gravel, snow, grass, etc.

[0006] The first step in this process is to compute a “perfect” average

20 of the diagonal ratio (the ratio of pulses accumulated on one front and its opposite rear over the total pulses). This computation must be performed when the vehicle is traversing a non-deformable surface, has zero acceleration, and is going straight. This “perfect” average is then used to generate a tire deformation adjustment to compensate for acceleration, deceleration, or

25 turning during data collection. This adjustment prevents the false triggering of a warning on tires that are lower than the nominal pressure, but still above the warning threshold. False triggering can be caused by the effect of weight transference due to acceleration, deceleration or cornering on tire rolling radius.

30 **[0007]** Three separate tests are performed to determine tire pressure loss. The first test covers any individual tire, opposing diagonal tires, or any combination of three low tires. The first step in this process is to compute an

average of the diagonal ratio. A requirement of this test is that the diagonal ratio stays within a narrow band. If the diagonal ratio goes outside of the acceptable band, the data is deemed unreasonable, and is not included in the average diagonal ratio. In the case of a rapid loss of pressure, the data will be

5 ignored initially, and then accepted when it meets the criteria of repeatability. If the data is deemed repeatable, the tire deformation adjustment is applied to it and a running average is formed. If the running average is greater than the calibration amount by more than the pressure loss threshold, a warning occurs. If the running average is less than the trigger point, a test is performed to

10 determine if a warning is currently set. If no warning is set, the routine proceeds to the multiple wheel tests. If a warning is set, the routine checks for constant speed and heading. If this criterion is met, the diagonal ratio is tested for being within three PSI of the “perfect” average computed previously. If this condition is met, the warning is cleared.

15 [0008] The two additional pressure loss tests cover the loss of pressure from both of the front, rear, left, or right tires. These multiple wheel tests require that the vehicle is not accelerating, decelerating, or turning. The algorithm looks for repeatability over several tenths of a mile to determine low tires. The distance test must be set to accommodate the longest curve likely to

20 be encountered. To perform this test, lateral and longitudinal distance ratios must be computed. The lateral ratio consists of the ratio of the pulses accumulated on one side of the vehicle to the total pulses. If the lateral or longitudinal ratios are greater than a calibration, then the routine resets the respective test odometer. When the longitudinal odometer counts down to

25 zero, the longitudinal ratio minus a speed related compensation is compared to a pressure loss threshold. A warning occurs if the threshold is exceeded, and is cleared if the longitudinal ratio is within three PSI of the nominal calibration. When the lateral odometer counts down to zero, the lateral ratio is compared to a pressure loss threshold. A warning occurs if the threshold is

30 exceeded, and is cleared if the lateral ratio is within three PSI of the nominal calibration.

[0009] The calibration mode is very strict about the data it will accept. It will not accept data during acceleration, deceleration, turning, or any non-repeatable data ratios. If the longitudinal ratio varies outside of a tight calibration, the algorithm rejects the data. If the vehicle is traversing a 5 deformable surface, the routine rejects the data. If the data passes both of these tests, tight repeatability criteria insure that the measurement is valid. The data from the calibration mode is used to compensate the incoming data to eliminate the effects of variation in tire loading, tire size, tire wear that are normally present.

10 **[0010]** Moreover, this invention will accommodate any steering angle, longitudinal acceleration, or lateral acceleration. In addition, this invention uses an adaptive method to eliminate false warnings by tracking variations in tire pressure that are less than the warning trigger point and adjusting the measurements based on the tire deformation characteristics due to acceleration 15 induced weight transference and/or vehicle load.

[0011] Advantageously, this invention will calibrate all four wheels during periods of zero longitudinal and lateral acceleration and adaptively correct for speed variations of all wheels.

20 **[0012]** Advantageously, this invention will trigger a warning upon reaching a predetermined pressure loss threshold and clear said warning without recalibration upon a tire reaching a predetermined recovery threshold. This is a self-clearing feature which clears the warning when a tire or tires are refilled to a predetermined level within the nominal calibration thresholds or when simply clearing a false trigger precipitated by a juxtaposition of unlikely 25 data events.

[0013] Advantageously, this invention will trigger a warning upon the rapid loss of tire pressure. This will allow detection of all types of pressure leakage, from a pinhole leak to a catastrophic failure.

30 **[0014]** Advantageously, this invention may reside in any vehicle controller or custom built controller that may receive digital pulses from an ABS system and/or a vehicle transmission at any regularly scheduled time interval by any available form of communication.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] This invention may be best understood by reference to the preferred embodiment and to the drawings in which:

5 **[0016]** FIG. 1 is a hardware diagram of a vehicle equipped with an anti-lock braking system having a rotation sensor on each wheel. In addition, said anti-lock braking system controller having communication with an additional controller in which (in this embodiment) the invention will operate. The secondary controller having communication with the vehicle to provide a 10 means to inform the vehicle operator through a driver information device of a loss of pneumatic tire pressure balance.

[0017] FIGS. 2-5 illustrate a sequence of operations that are executed to carry out the tire pressure warning method function outlined in FIG. 1.

15 **DESCRIPTION OF THE PREFERRED EMBODIMENT**

[0018] A method and apparatus for detecting under-inflated tires for a vehicle using distance traveled by each of the tires. For the purposes of this invention, only the mechanical and electrical components are shown. In the preferred embodiment, as shown in FIG. 1, a vehicle 18 is equipped with an 20 Anti-lock Braking System (ABS) and a means to sense all four wheel rotations. Alternatively, the method does not require an ABS system. The method requires at a minimum that wheel rotation sensors are included as well a means of measuring the rotation sensor signals in a controller. The rotation sensor generates a predetermined number of pulses for each revolution of the 25 wheel as in an ABS system.

[0019] Referring to FIG. 1, when the left front tire 1 and the matching wheel bearing 5 rotate about an axis, a motion sensor 19 which includes an integrated machined tooth passes a mounted proximity sensor 9 generates a rising edge digital pulse upon first contact and a falling edge digital pulse 30 when the tooth is no longer within the sensor's proximity. An ABS controller 13 receives the rising and/or falling edge digital pulses for each wheel and accumulates the sum of these pulses for each wheel. The ABS system

communicates the sum of the digital pulses of each individual wheel to the Body Control Module (BCM) 14 by way of an ordinary serial data interface 15, at regular intervals. The same can be said of the remaining wheels, where the combination of tire and wheel 2, wheel bearing 6, and sensor 10, represent 5 the right front assembly, wheel 3, wheel bearing 7, and sensor 11, represent the left rear assembly, and wheel 4, wheel bearing 8, and sensor 12, represent the right rear assembly. When the sequence of operations as outlined in FIG. 2 determine that a tire or tires are in a state of rotational error because of tire pressure loss, the BCM controller 14 issues a message to the driver 10 information device 16 by way of an ordinary serial data interface 17.

[0020] Since this invention is based solely on the distance traveled, a more detailed description of the properties of this invention follows. The method is based solely on the measured distance traveled by each tire. The quantity of machined teeth and rolling circumference of each wheel 15 determines the relationship between sensor pulses and distance. It is well known that a deflated tire has a smaller rolling radius. The basis for this invention is that an under-inflated tire will rotate more than a properly inflated tire. For example, if we have a vehicle having four matching fifteen inch steel belted radial tires, with one tire having a pressure of ten PSI less than the other 20 three tires, then the under-inflated tire will need to rotate the equivalent of 2.8 feet more than the three properly inflated tires will in one-tenth of a mile. One rotation of this tire measures 6.3 feet and produces forty-eight digital pulses in that distance. In one-tenth of a mile, these tires rotate approximately eighty-four times with each tire producing four thousand and thirty-two digital pulses. 25 The additional 2.8 feet of travel of the under inflated tire will produce an extra twenty-one digital pulses in one-tenth of a mile or one extra digital pulse every four wheel rotations.

[0021] The pulse counting method has the inherent ability to function properly at any vehicle speed, on any surface, and relatively noise free under 30 adverse driving conditions. A substantial advantage of this method is that it may be utilized in any vehicle controller, as long as it receives the wheel pulse count at regular intervals. This method does not require high throughput and

may operate on any real time interrupt time base. Time between teeth is not used.

[0022] Referring to FIG. 2, a method of detecting under-inflated tires by measuring the rotational variation of vehicle wheels is diagrammed to

5 illustrate the control processes of this embodiment. Referring to FIG. 1, wheel rotation is measured by the ABS controller 13 and all of the digital pulse transitions from proximity sensors 9, 10, 11, and 12, are accumulated by the controller 13 and the individual sums of each wheel transmitted to the BCM 14 at a convenient time interval.

10 [0023] At every interval of one hundred milliseconds, for example, a series of controller instructions generally illustrated by the operations of FIG. 2 starting at step 20 and proceeding to step 25 are executed. At step 25, all of the digital pulses of every individual wheel are received and stored into an individual account bearing the names of: left front (LF), right front (RF), left

15 rear (LR), and right rear (RR) in a storage device. In step 30, determination is made as to whether the calibration switch is depressed. If it is determined that the calibration switch is on, calibration mode is enabled by setting *CalMode=True*, and *KDAIG=KDAIG2=Kdcal*, in step 35, as discussed more fully below.

20 [0024] At every interval of one hundred milliseconds, for example, a series of controller instructions generally illustrated by the operations of FIG. 2 starting at step 20 and proceeding to step 25 are executed. At step 25, all of the digital pulses of every individual wheel are received and stored into an individual account bearing the names of: left front (LF), right front (RF), left

25 rear (LR), and right rear (RR) in a storage device. In step 30, determination is made as to whether the calibration switch is depressed. If it is determined that the calibration switch is on, calibration mode is enabled by setting *CalMode=True*, and *KDAIG=KDAIG2=Kdcal*, in step 35, as discussed more fully below.

30 [0025] If step 45 determines that the wheels are not slipping, then the system proceeds to step 50, where the new digital pulse information is summed, *LFT=LFT+LF*, *RFT=RFT+RF*, *LRT=LRT+LR*, *RRT=RRT+RR* and

$dist=LFT+RFT+LRT+RRT$. This is followed by step 60, which determines whether one or more complete revolutions of all wheels - the short distance occurred a complete revolution has occurred and if the total number of digital pulses are greater than calibration $KSHORTD$, the routine proceeds to step 70

5 which calculates several parameters to allow a determination to be made of the acceptability of the data thus far collected. If not, the system proceeds to step 640 to wait for the next time period.

[0026] The next steps, 80-110, determine the suitability of the data for determining tire pressure imbalance. A series of steps are performed to see if 10 the vehicle is stable. Typical criteria used are: lateral acceleration below a threshold (step 80), turning radius above a limit (step 90). At step 110, the difference between the *diagonal ratio* and the average value of this parameter calculated at steps 220-260 is used to eliminate data that is impossible to achieve due to pressure imbalances. The *diagonal ratio* is the ratio of the 15 distance traveled by the left front and right rear tires over the distance traveled by all of the tires. This is done by summing the pulses for the wheels. If any of the required criteria are not met, the algorithm proceeds to step 140, where the values are reset. If the data accumulated thus far is acceptable, at step 150 this data is further aggregated into sums *LFA*, *RFA*, *LRA*, and *RRA*. At step 20 160, a determination is made to determine if a second total distance has been accumulated.

[0027] If the second required distance has been achieved ($KMIDD$), then at step 170, additional calculations are made to allow the following steps to determine the validity of the data. At step 180, the *longitudinal ratio*, 25 which is the ratio of the distance traveled by the front wheels over the total distance traveled by all of the wheels, is used to determine if the vehicle is on a loose surface. Again, this is done by using the number of pulses. An additional compensation is made in step 180 to account for the additional distance the driven wheels of a vehicle will travel due to the tractive slip 30 required to maintain vehicle velocity. This compensating factor is generally related to the speed of the vehicle when the data is recorded. If the vehicle is on a loose surface, the data is only accepted if the diagonal ratio is repeatable

within a tolerance (*KDIAGREP*) at step 120, and not outside of a bound (*KDAIG2*) with respect to the average value of the *diagonal ratio* in step 130.

[0028] If the data meets the previous criterion, a last pulse accumulation is made to form the sums *LFS*, *RFS*, *LRS*, *RRS* at step 190. The 5 acceleration, lateral acceleration and speed are also accumulated to keep track of the vehicle conditions as each record is added to the final sum. If at step 200, the distance *LONGD* (typically .05-.2 miles) has been achieved, then the routine proceeds to step 210. At this point, the previous values of the ratios are saved and the *longitudinal*, *diagonal* and *lateral ratios* are calculated. The 10 *lateral ratio* represents the ratio of the distance traveled by the left side tires over the distance traveled by all of the tires. At steps 220-260, an average value of the *diagonal ratio* is created by using data only when the vehicle is traveling in a very consistent manner. This is typically determined by low acceleration (step 220), low lateral acceleration (step 230), and repeating 15 values of the *diagonal ratio* (step 250). At step 260, the new data is averaged into the old to form the value *AvgDiag*.

[0029] At step 270, compensations are calculated to prevent false pressure imbalance detection caused by acceleration or turning. The basis for this compensation is the characteristic that a low-pressure tire will deform 20 more than a properly inflated one, under loading from weight transfer caused by vehicle maneuvering. Without this compensation, a tire that is low, but above the detection threshold, could appear lower than the limit during maneuvers, giving a false or premature warning. At step 280, if the diagonal ratio is repeating within a narrow band, a running *diagonal ratio* average is 25 created using the current value of the *diagonal ratio*. Additionally, in step 290, the pressure loss variable is calculated using the running average and the calibrated value of the *diagonal ratio* as well as the compensations calculated previously. It should be noted that the calibrated values of the *diagonal ratio*, *lateral ratio*, and the *longitudinal ratio* represent the values of these factors 30 when the tires are in a known nominal state i.e. when the pressures are correct. The difference between these calibrated values and the current value of these ratios are generally proportional to the pressure imbalance being measured. If

the *diagonal ratio* is not repeating within the band $Krepeat$, then in step 300, the running diagonal ratio is updated with the value $AvgDiag$, which represents the current value of the diagonal ratio when no maneuvers are occurring. In this way, the running average is prevented from being corrupted

5 by vehicle conditions that could lead to false warnings. At step 310, the calculated pressure imbalance is compared to the desired threshold, $Ktrip$. If the limit is exceeded, an alert is indicated at step 320. If the pressure loss is below the threshold, step 330 determines if a warning is already in effect, if so, at steps 340-350, a determination is made if the alert should be cancelled.

10 The alert is set to OFF at step 360 if the running average is close to the value $AvgDiag$ and the calculated pressure loss is below the value $Ktripoff$. At step 370-380, a determination is made if the vehicle is changing speed or turning, if so, no further pressure loss checks are performed and the routine exits to step 570.

15 **[0030]** Steps 390-470 are used to detect the simultaneous loss of pressure in two tires on the same side of the vehicle. This type of pressure loss is difficult to determine using wheel rotation data because the effect of this type of pressure imbalance is the same as the effect of a vehicle performing a turn. At steps 390-410, the lateral ratio is checked to determine

20 if it is repeating within a narrow band ($Klat$) at least $Kcnt$ times in a row. If the value repeats as required, the routine proceeds to step 420, otherwise it exits to step 480, clearing the counter if appropriate. At step 420, a comparison is made to determine if the loss alert should be set to ON. The comparison is based on the difference between the calibrated value of the

25 lateral ratio and the current filtered value. If the pressure loss is above $Ktrig$, the repeat counter is cleared at step 450 and the warning set at step 460. If the calculated pressure loss is below the level to set the warning, at step 430, the loss is compared to the calibration $Ktripoff$ to determine if the warning should be cleared. If required, the warning is cleared at step 440.

30 **[0031]** Steps 480-560 are used to detect the simultaneous loss of pressure in two tires on the same end of the vehicle. This type of pressure loss is difficult to determine using wheel rotation data because the effect of this

type of pressure imbalance is the same as the effect of a vehicle traveling in a situation where a large amount of power is required to maintain speed. Some examples are driving at high speed, climbing a long grade or towing. At steps 480-500, the compensated value of *longitudinal ratio* is checked to determine

- 5 if it is repeating within a narrow band (*Klong*) at least *Kcnt* times in a row. If the value repeats as required, the routine proceeds to step 520, otherwise it exits to step 570, clearing the counter if appropriate. At step 520, a comparison is made to determine if the loss alert should be set to ON. The comparison is based on the difference between the calibrated value of the
- 10 longitudinal ratio and the current filtered value. If the pressure loss is above *Ktrig*, the repeat counter is cleared at step 530 and the warning set at step 540. If the calculated pressure loss is below the level to set the warning, then at step 550, the loss is compared to the calibration *Ktripoff* to determine if the warning should be cleared. If required, the warning is cleared at step 560.
- 15 The routine then proceeds to step 570, where a check is made to see if the calibration mode is in effect. If the calibration mode is not active, the routine is complete at step 640.

[0032] In calibration mode, at steps 580-590, each of the ratios is checked for repeatability within the band *Kcal*. Any ratio that varies outside

- 20 this band causes the process to proceed to step 640 to wait for the next time period. At step 595, *calcnt* is checked to determine if the values of *A1*, *A2*, *A3*, need to be initialized, if this is the first execution of the calibration routine, at step 600 the ratio averages are initialized. At step 610, the counter *calcnt* is incremented and a running average created for each of the three ratios:
- 25 *lateral*, *longitudinal* and *diagonal*. The routine proceeds to step 620, where the value of *calcnt* is compared to *Kcalrep* to determine if the required number of repeating ratios has occurred to allow the determination of a valid calibration. At step 630, the running ratio averages are stored in the respective variables *LatCal*, *LongCal*, and *DiagCal*. In addition, the several other
- 30 variables are initialized and the calibration mode is completed. The routine then goes to step 640 where it remains dormant until the next real-time interrupt, which will begin execution at referenced step 10.